

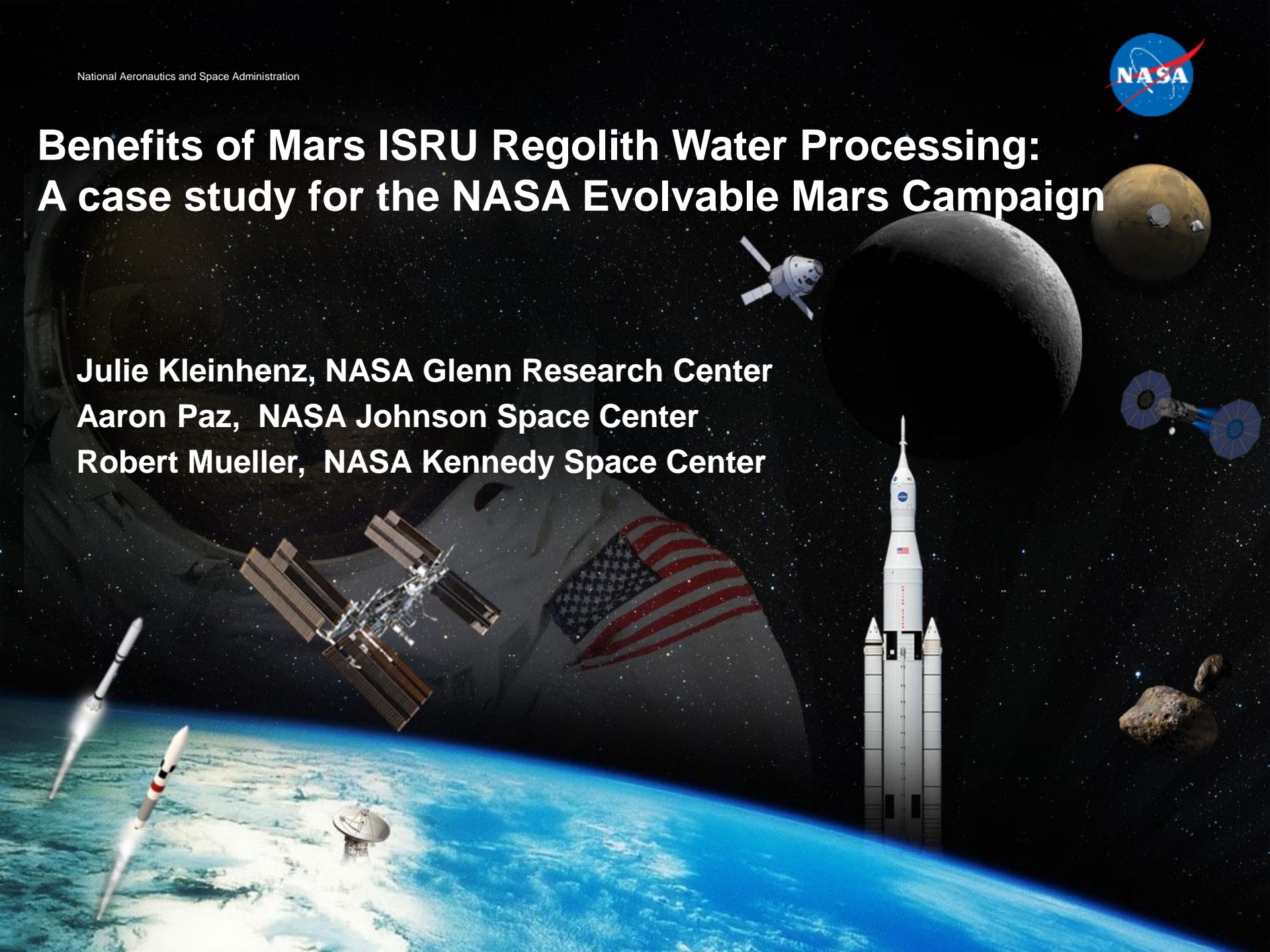


Benefits of Mars ISRU Regolith Water Processing: A case study for the NASA Evolvable Mars Campaign

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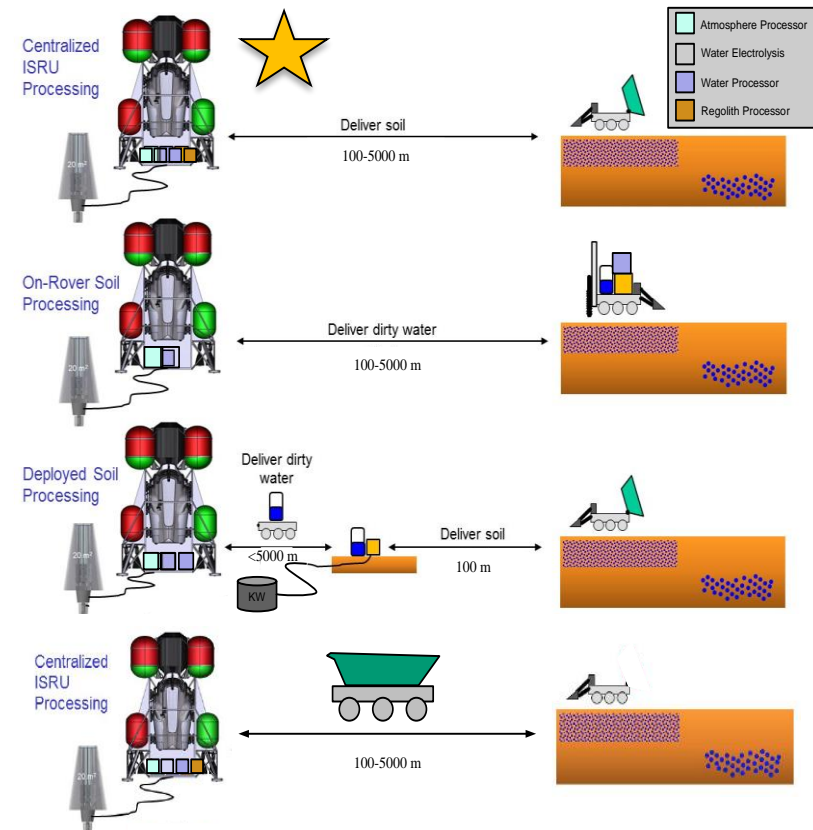


- **ISRU of Mars resources was baselined in 2009 Design Reference Architecture (DRA) 5.0, but only for Oxygen production using atmospheric CO₂**
 - The Methane (LCH₄) needed for ascent propulsion of the Mars Ascent Vehicle (MAV) would need to be brought from Earth
- **HOWEVER: Extracting water from the Martian Regolith enables the production of both Oxygen and Methane from Mars resources**
 - Water resources could also be used for other applications including: Life support, radiation shielding, plant growth, etc
 - Water extraction was not baselined in DRA5.0 due to perceived difficulties and complexity in processing regolith
- **The NASA Evolvable Mars Campaign (EMC) requested studies to look at the quantitative benefits and trades of using Mars water ISRU**
 - Phase 1: Examined architecture scenarios for regolith water retrieval. Completed October 2015
 - Phase 2: Deep dive of one architecture concept to look at end-to-end system size, mass, power of a LCH₄/LO₂ ISRU production system

Approach



- Water bearing regolith is retrieved using a mobile excavator and delivered to a centralized ISRU processing plant.
- ISRU processing plant is co-located with the Lander and MAV.
- Use current EMC projections to define ISRU production needs
- Generate a system model to roll up mass & power of a full ISRU system and enable parametric trade studies.
 - Use previous studies and technology development programs to select baseline subsystems/components for this study
 - Use existing hardware with mass/power/performance to provide a basis for subsystem level trades in future studies
 - Whenever possible used reference-able (published) numbers for traceability, as opposed to 'real-time' working numbers.



Top level production requirements



- Propellant mass needs taken from most recently published MAV study:
 - Polsgrove, T. et al. (2015), AIAA2015-4416
- MAV engines operate at mixture ratios (oxygen:methane) between 3:1 and 3.5:1, whereas the Sabatier reactor produces at a 4:1 ratio. Therefore:
 - Methane production is the driving requirement
 - Excess Oxygen will be produced

- Production rate based on a mission timeline of 480 days (16 months)
 - ISRU system arrives one launch opportunity ahead of humans
 - MAV must be fully fueled before human departure from earth

26 month launch opportunity

– 9 month transit time

– 1 month margin

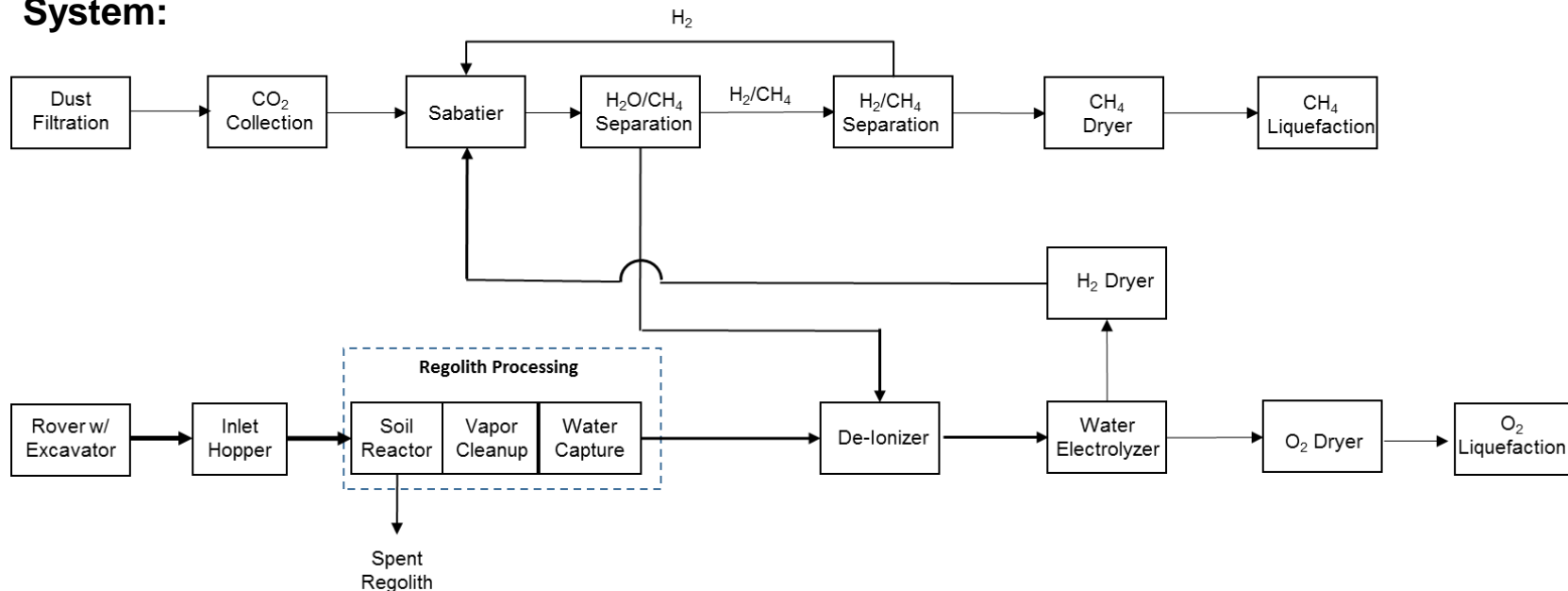
16 months

		Total mass needed	Rate at 480days continuous operation
Requirement:	CH ₄	6978 kg	0.61 kg/hr
Reactants needed to meet requirement:	H ₂ O	15701 kg (785,050 kg 2% soil)	1.36 kg/hr (68.2 kg/hr soil@2%)
	CO ₂	19190 kg	1.67 kg/hr
Results in:	O ₂	27912 kg total (22728 kg propellant, 1906 kg Life support, 3278 kg leftover)	2.43 kg/hr

Assumptions



- **Production Rate driver: 6978 kg of Methane needed + 0.5% margin**
 - Methane is the driver since excess oxygen will be produced using Sabatier process
- **Time of ISRU production: 480 day operation, 24hr/day**
- **Soil Water resource (baseline): Water from surface regolith = hydrates** Ubiquitous (location independent), Available in surface material (subsurface excavation not required), Lower resource yield is more of a worse case for water extraction system
- **Liquefaction: Takes place in the MAV tanks.** ISRU system only includes mass/power for crycoolers needed to liquefy. MAV responsible for tanks and zero boil-off systems
- **Power Source: Not part of ISRU system.** Assumes a fission reactor will be needed for human presence, ISRU will use reactor when humans are not present. (TBD- negotiations to occur as power needs are identified)
- **Radiators: Not part of ISRU system.** ISRU will be packed on lander.
- **System:**



Subsystem Selection for this study



Subsystem	Components	Heritage
Excavation	RASSOR 2.0 excavator concept prototype	KSC hardware (2015 Phase 1)
Soil Processing	Size Sorter / Auger Conveyor reactor	JSC design concept (2015 Phase)
	Soil hopper/Size Sorter prototype	KSC hardware –sized & tested
	Vapor cleanup	Nafion, COTS
	Water collection: Coldtrap	JSC design concept
CO2 Acquisition	Cryocooler	Cryotel GT, COTS, KSC cold head
Sabatier	Microchannel Sabatier	Battelle PNNL (SRP study)
	CH4/H2O separator	-sized-
	CH4/H2 separator	Hamilton Sunstrand (MIST)
Electrolysis	PEM electrolysis stack, Cathode feed	Giner Inc., COTS (HESTIA)
	Deionizer	GE, COTS
	H2/H2O separator	-sized-
	Inlet pump	Micropump, COTS
	Regenerative Gas drier, desiccant	JSC hardware
Liquefaction	Cryocooler	Cryotel GT, COTS
	Tanks	-sized-

Sizing: LO₂ and LCH₄ ISRU System



Approach: Production requirement met by 3 independent ISRU systems including:

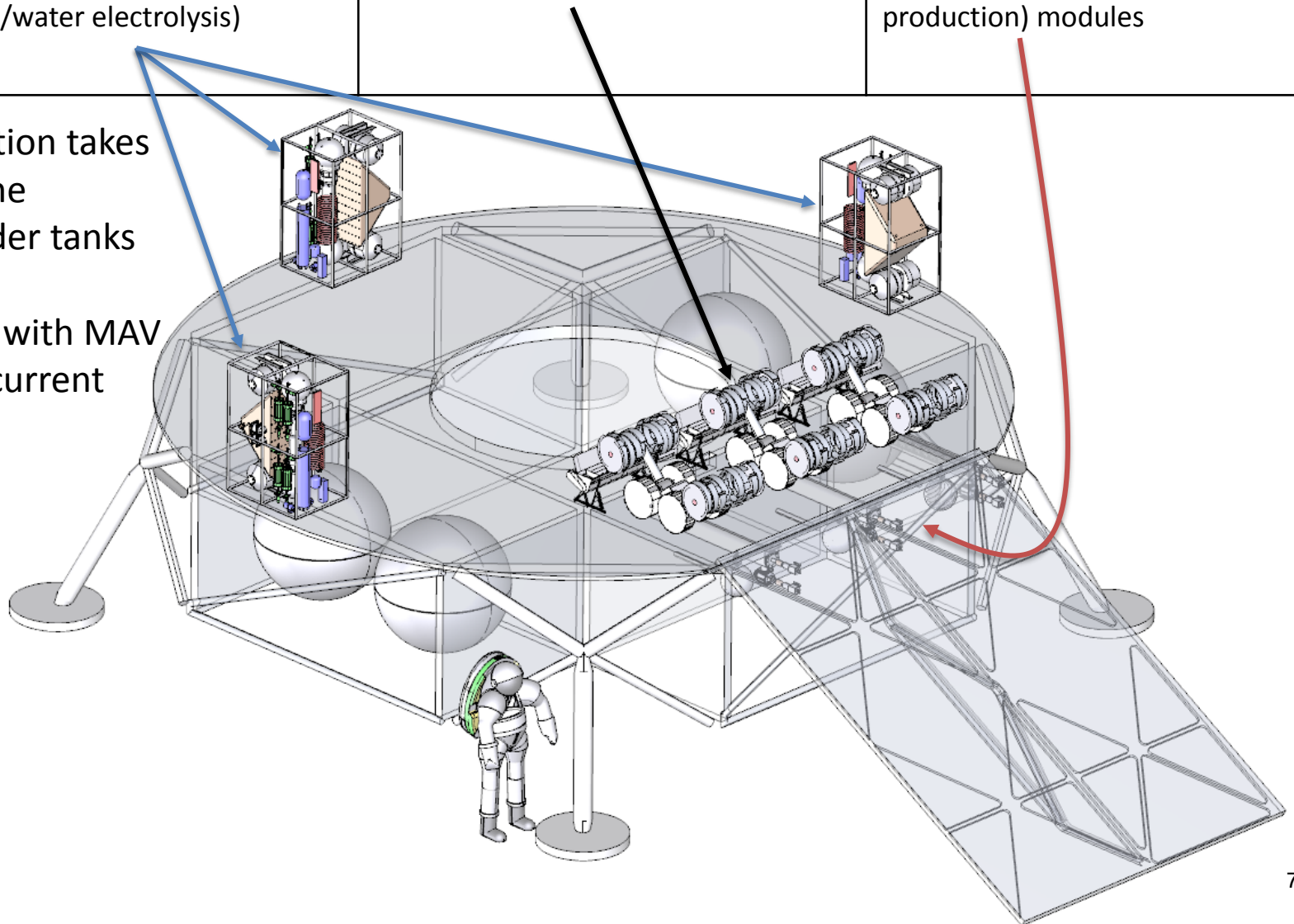
3 Propellant production (atmosphere processing/water electrolysis) modules

3 mobile RASSOR excavators

3 regolith processing (water production) modules

*Liquefaction takes place in the MAV/Lander tanks

*Working with MAV team for current packaging

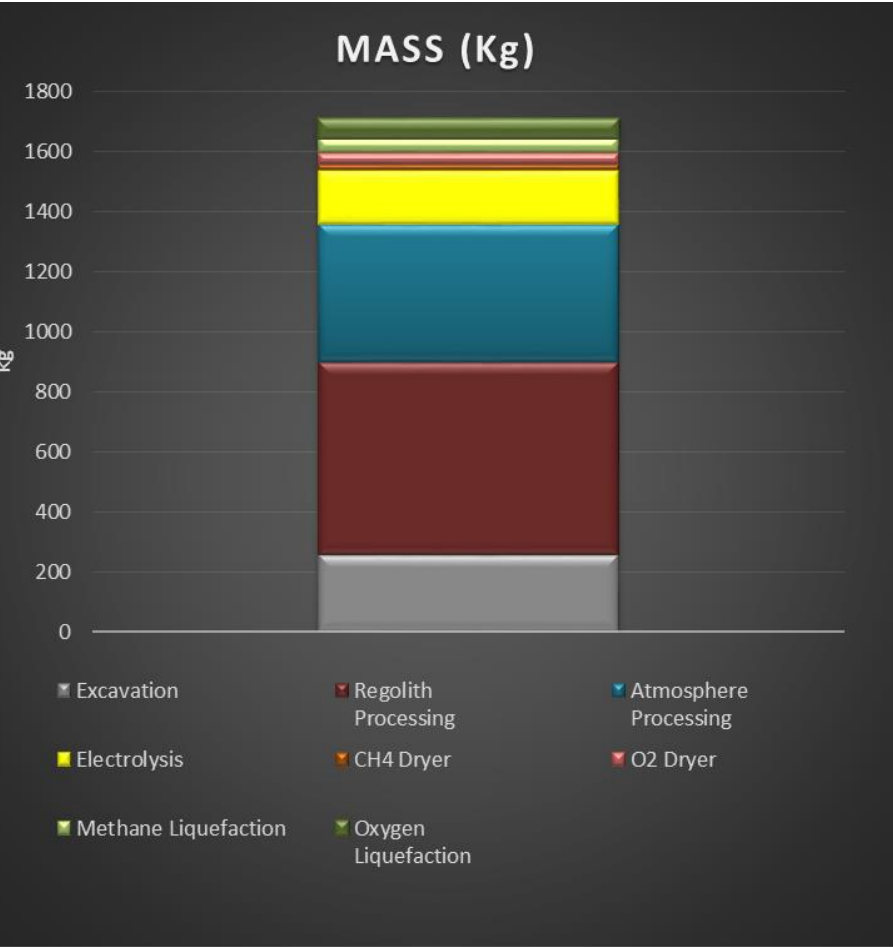


Total ISRU system (3 modules)

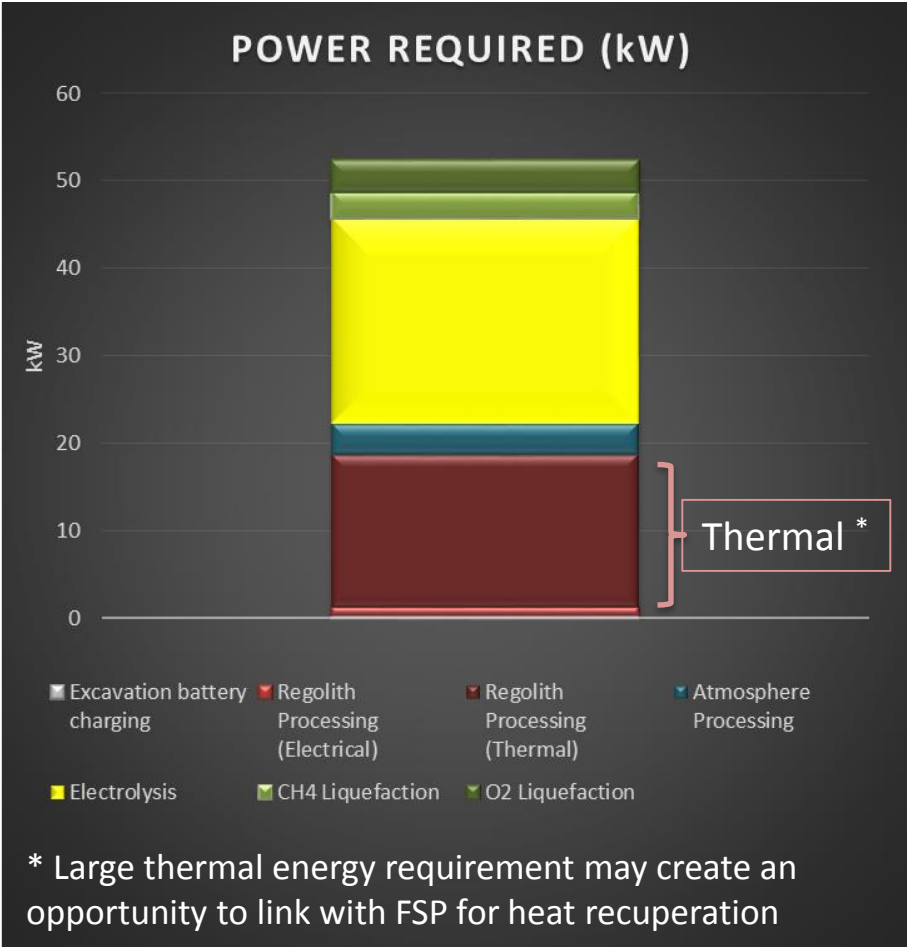


Baseline case, Assumptions:

3 independent ISRU systems each producing 40% of the needed products, 15% mass added for structure, 20% margin added to power and mass, Garden variety (common globally on Mars surface) regolith with 1.26wt% water processed at 300C



Total Mass: 1708 kg



* Large thermal energy requirement may create an opportunity to link with FSP for heat recuperation

Total Power: 52 kW

Regolith needs for Baseline case



	Total needed for mission		Amount needed <u>per</u> <u>module</u> (assuming 3 independent modules)		Amount needed <u>per module</u> <u>per day</u>		Delivery capabilities <u>per Rassor</u> <u>per day</u> * (using baseline assumptions)
Mass of Regolith	1500 MT	➔	500 MT	➔	1.04 MT	↔ compare	2.3 MT
# of Rassor batches	14797 batches		4932 batches		11 batches		23 batches

Using the current assumptions 1 Rassor excavator per module is more than sufficient to meet production needs.

(If assumptions are changed, the system model is designed to adjust the number of excavators needed and this would be reflected in mass/power)

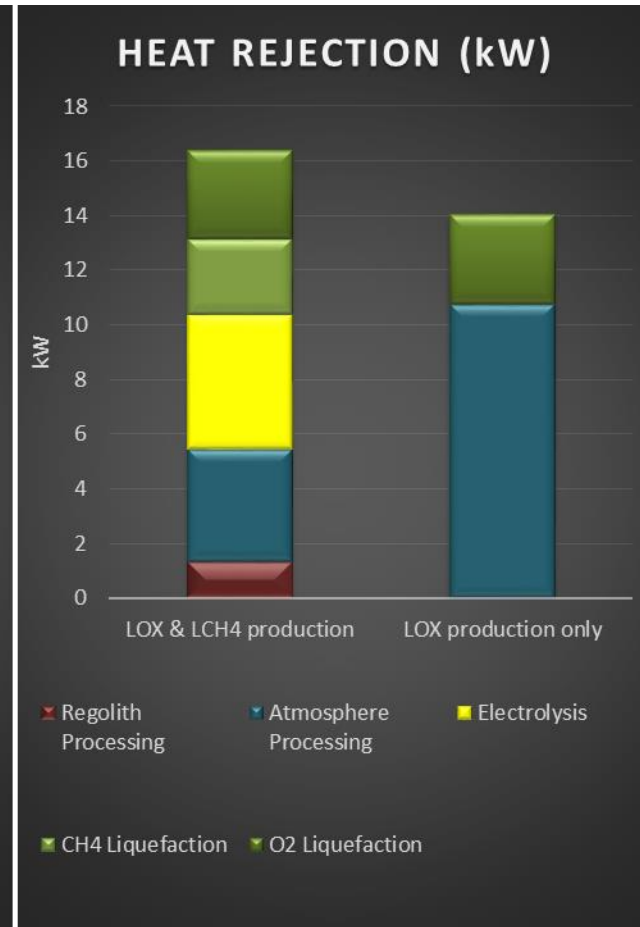
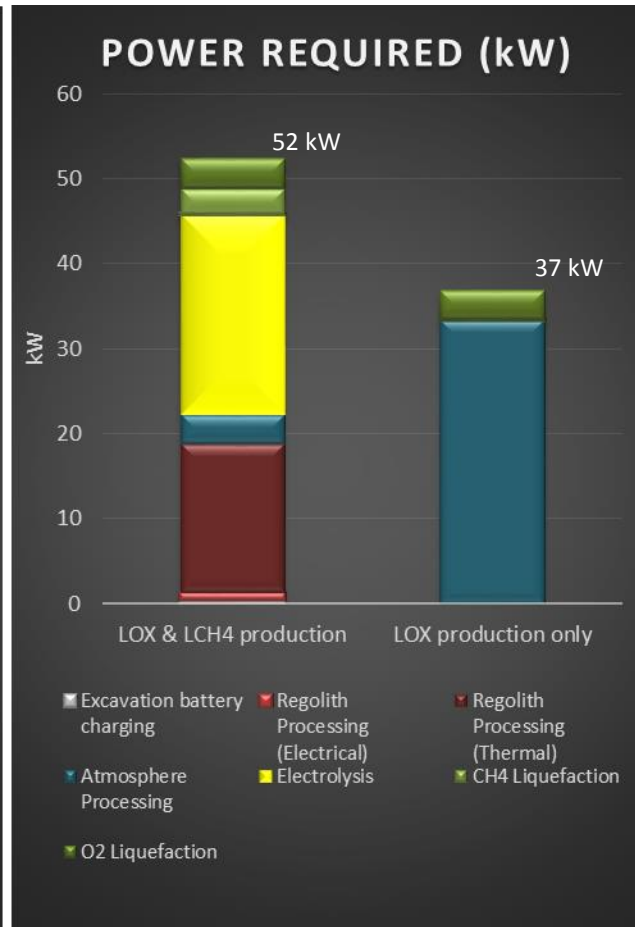
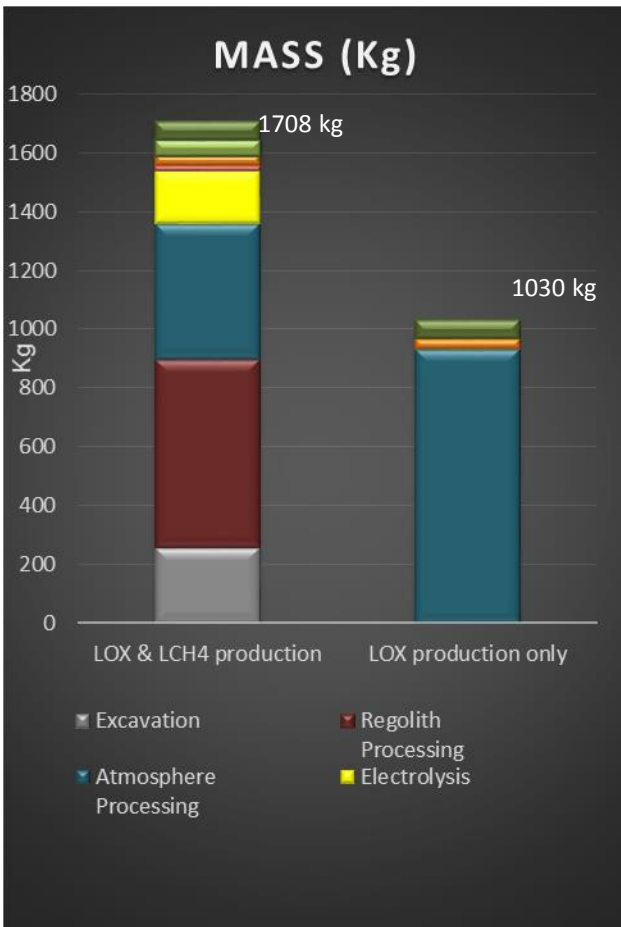
*Assumptions:

- Conops: 5 hrs = 5 batches + battery recharge (Assuming the resource is 100m away, the rover travels at 0.26 m/s, and excavation time from laboratory tests.)
- Each Rassor batch delivers 9.7% of the needed regolith per day per module. (Based on volumetric capacity of Rassor bucket and regolith bulk density of 1.9g/cc as suggested by MWIP team, Rassor can delivery 100kg per batch)

Comparison to Oxygen-Only ISRU plant



- **Assumptions: 3 independent ISRU systems each producing 40% of the needed products, 15% mass added for structure, 20% margin added to power and mass.**
- O₂-only system assumes a cryofreezer for CO₂ extraction and Solid Oxide Electrolysis for conversion



66% higher mass

42% higher power

17% more waste heat

M-WIP - Definition of Reference Reserve Cases



Essential Attribute	Deposit Type			
	A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	3 m	0 m	0 m	0 m
geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburden	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum ¹	40% smectite ²	23.5% basaltic glass ³
–Phase 2	--	3.0% allophane ⁴	3.0% allophane ⁴	3.0% allophane ⁴
–Phase 3	--	3.0% akaganeite ⁵	3.0% akaganeite ⁵	3.0% akaganeite ⁵
–Phase 4	--	3.0% smectite ²	3.0% akaganeite ⁵	3.0% bassanite ⁶
–Phase 5	--	--	--	3.0% smectite ²
Geotechnical properties				
–large-scale properties (“minability”), e.g. competence, hardness	competent--hard	sand--easy	sand--easy	sand--easy
–fine-scale properties (“processability”) , e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration

1. ~20 wt% water, 100-150°C
2. ~4 wt% water, 300°C
3. ~1 wt% water, >500°C
4. ~20 wt% water, 90°C
5. ~12 wt% water, 250°C
6. ~6 wt% water, 150°C

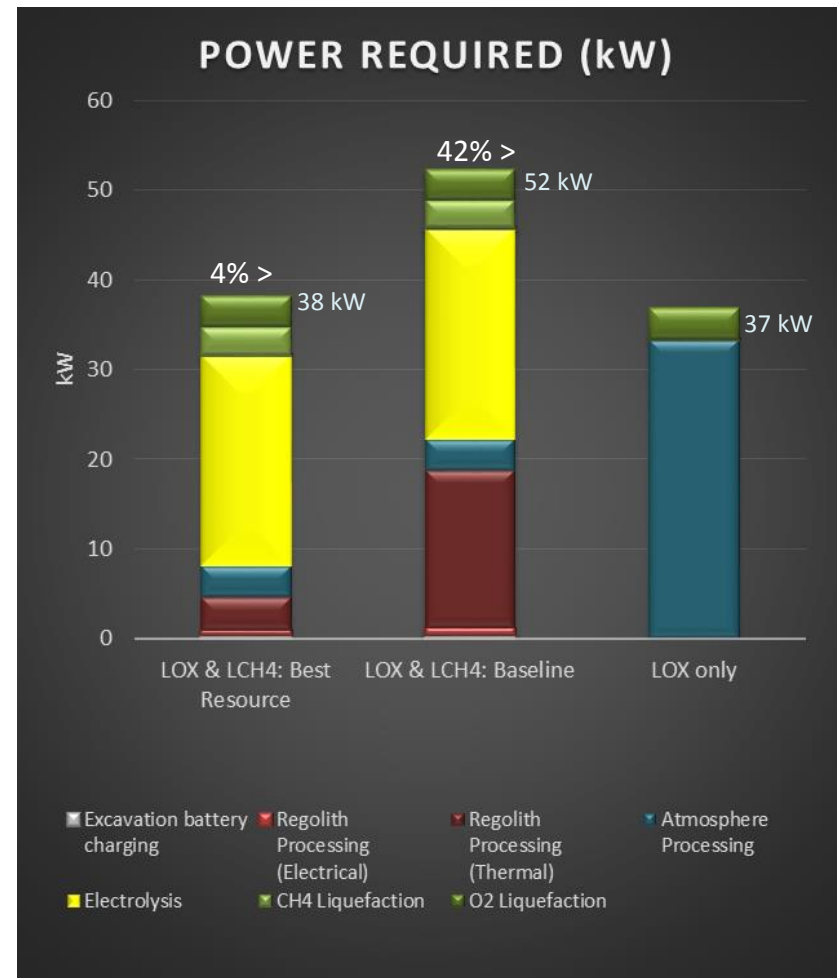
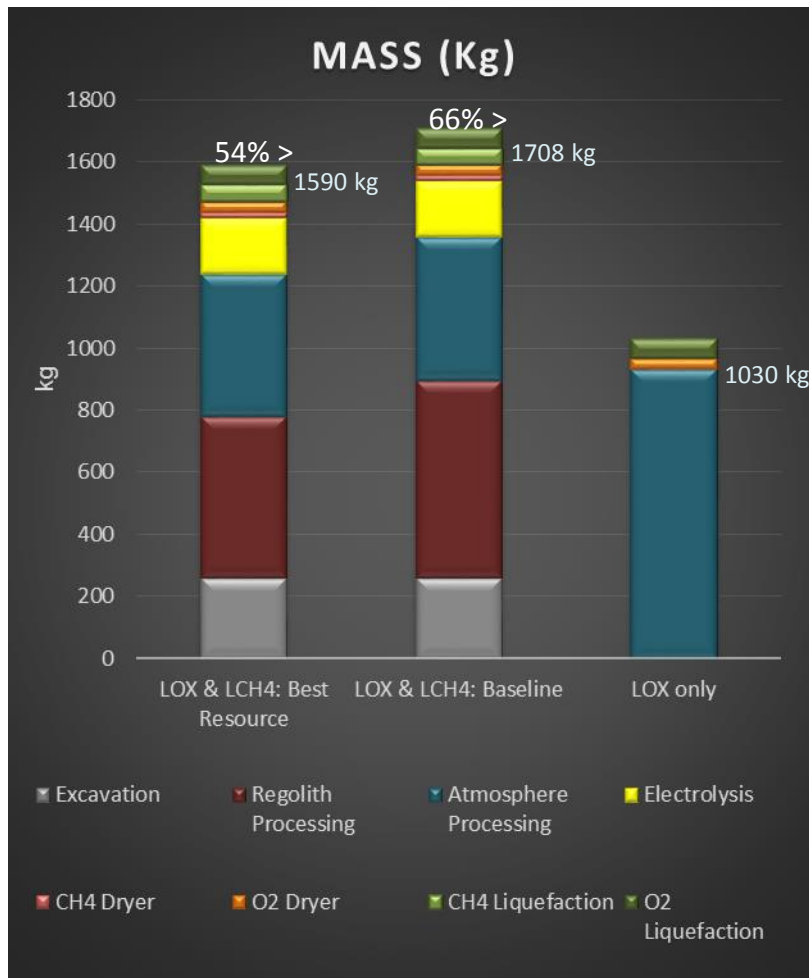
The M-WIP (Mars Water ISRU Planning) study is lead by SMD/Mars Program office and involves academy and industry members. The ISRU team has been working closely with these team to identify impacts of Mars resources and their location, and the data still needed to best define them.

- The MWIP team report is projected for released March 31,2016
- Information from the MWIP team has been incorporated into this study and visa/versa
- Other information from the MWIP team that will be leveraged for future work includes
 - Distance of resource versus excavation efficiency and Depth of resource versus overburden removal (trade)
- This slide shows the reference case resource possibilities. Case D was baselined in this Lox/LCH4 study. The following trades show the impact of Case B (best case granular deposit)

Trade: higher yield regolith



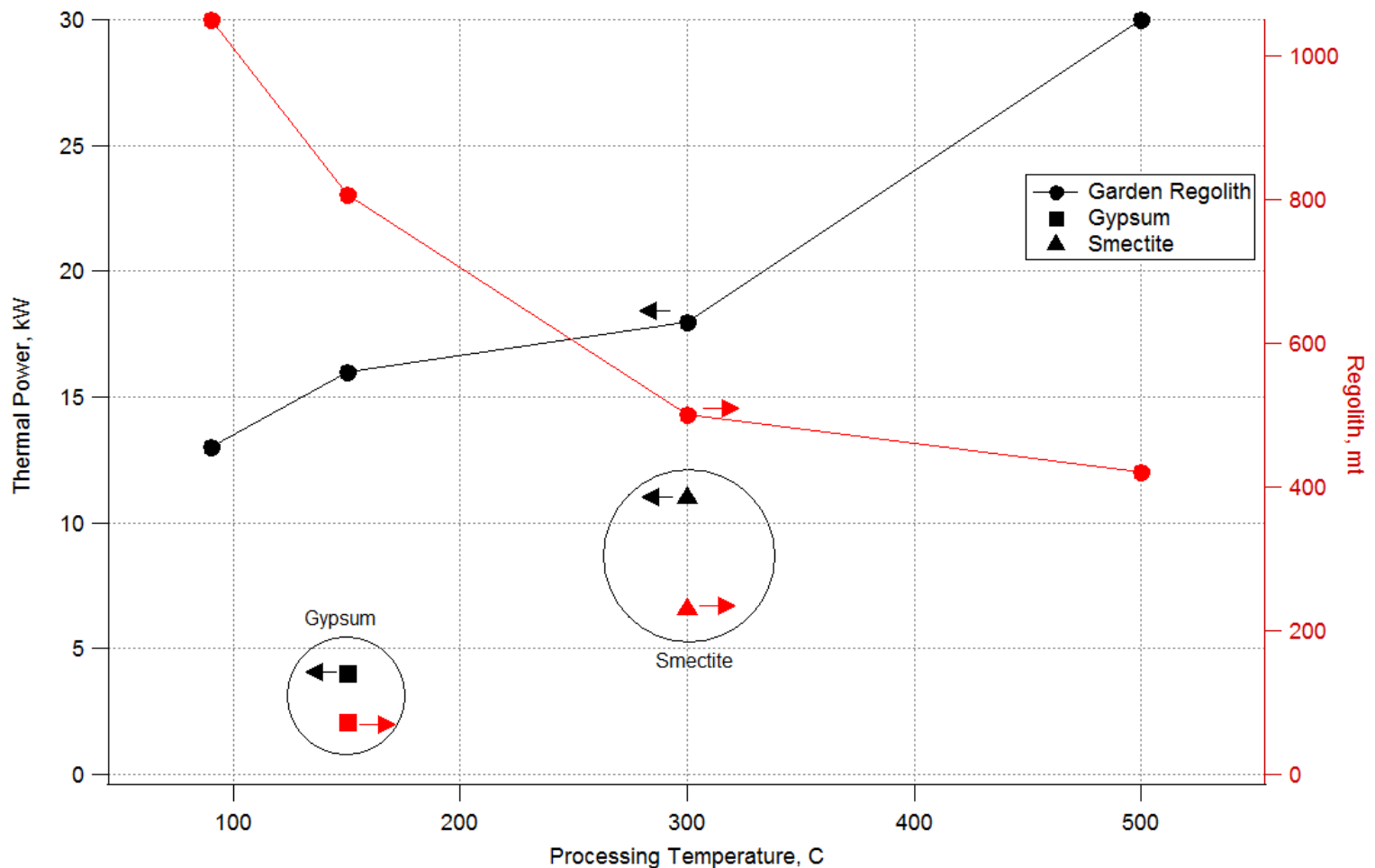
- The MWIP team has identified Reference cases for soil-water resources. The best case is that of a Gypsum deposit which has 8 wt% water releasing at 150C.
 - The percentages on the graphs show the increase over the LOX-only case
 - Targeting water-Rich deposits offers marginal mass improvement, but significant power reduction



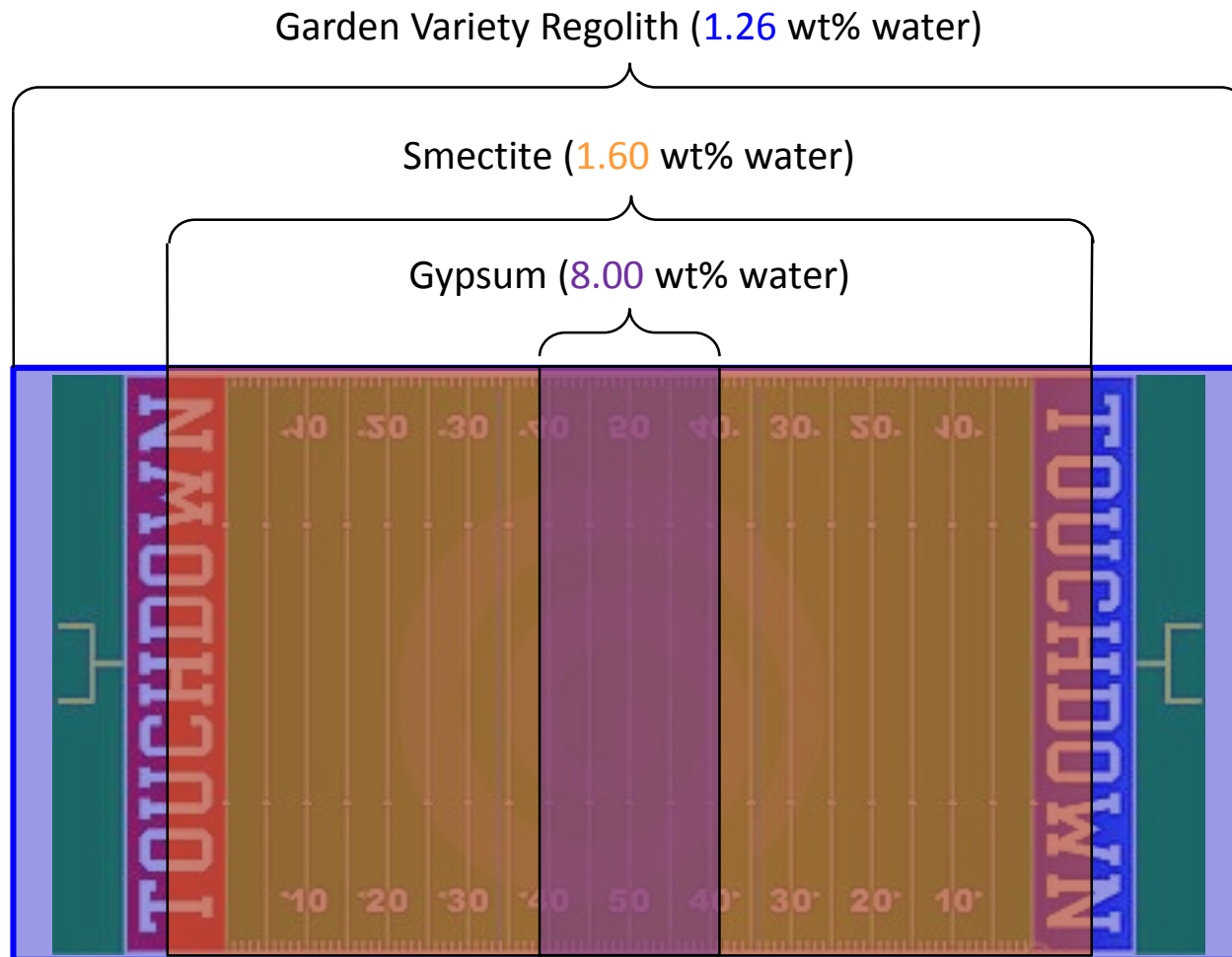
Trade: higher yield regolith



- The real benefit of targeting higher yield regolith is the power saving
 - Less regolith to heat
 - Heating at a lower temperature



Human Mission Mars Soil Excavation for Water



Surface area required per mobile excavator with the following assumptions:

- 3 mobile excavators used
- Each excavator provides 40% of required water
 - Excavation depth = ~5cm (2.0 in)

Mass comparisons

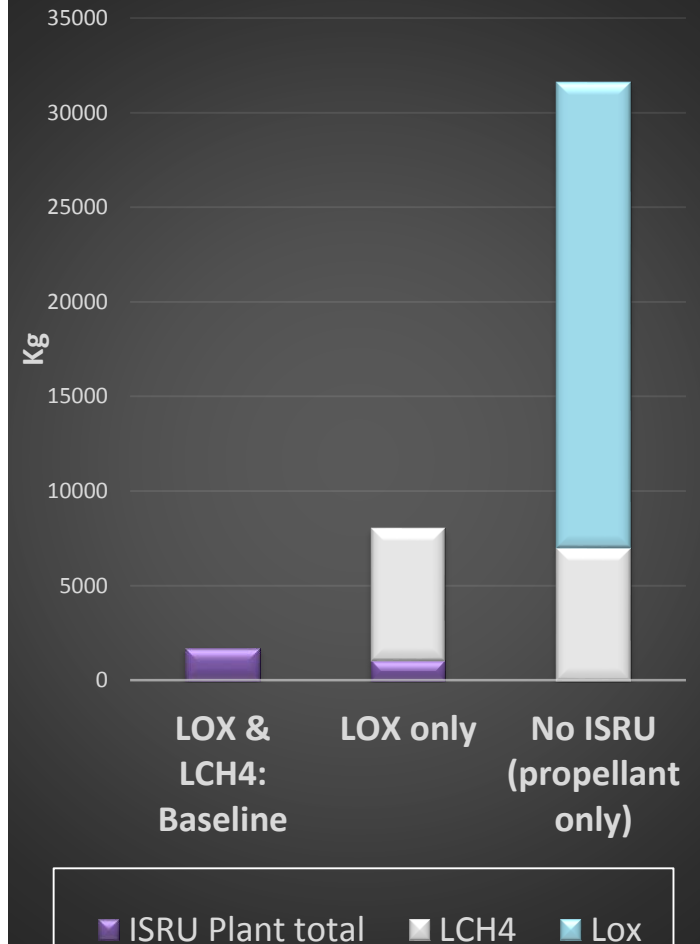


ISRU system Mass Comparison

The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.

	Hardware Mass, mt	Total Mass, mt (ISRU Hardware + Propellant from Earth)	Ratio: Propellant produced per kg of landed mass
<u>Case 1</u> ISRU for LO ₂ & LCH ₄ : Sulfates	1.6	1.6	22.1
<u>Case 2</u> ISRU for LO ₂ & LCH ₄ : Regolith	1.7	1.7	20.5
<u>Case 3</u> ISRU for LO ₂ only (no water)	1.0	8.0 (1mt hardware + 7mt Methane)	3.1
<u>Case 4</u> Propellant only (no ISRU)	NA	31.6 (24mt Oxygen + 7mt Methane)	NA

Landed Mass Comparison



For every kilogram of landed mass

(hardware mass + including terrestrial propellants):

- A LO_2/LCH_4 ISRU system can produce 20 kg of propellant
- A LO_2 -only ISRU system can produce 3 kg of propellant

Harnessing the Mars regolith water for ISRU offers a **6x improvement** over Mars ISRU atmosphere processing alone.

- *These calculations only account for the mass of the propellant that is needed in the MAV. They do not account for the additional propellant mass which would be required to deliver that MAV propellant to Mars from LEO. Thus the advantage of a combined ISRU LOX /Methane production system would be greater than indicated.*
- *Component/Technology trades in the ISRU end-to-end system may also offer an improvement*

This results in about mass savings in LEO on the order of 10kg for every kg of mars produced propellant

Targeting Water-rich landing sites (eg Gypsum deposits) offers only a marginal mass benefit, but reduces the power such that it is comparable to the LO_2 -only case (30% less power than the baseline regolith case).



Back up

Operational Assumptions



Liquefaction: (CH₄ liquefaction, O₂ liquefaction)

The ISRU liquefaction system only accounts for cryocoolers needed to liquefy the propellants. Liquefaction is assumed to occur in MAV ascent tanks so Tank mass and liquid maintenance is accounted for in MAV.

O₂ at 60K 15psi, CH₄ at 100K 50psi

Atmospheric processing: (CO₂ cyrofreezer, Sabatier reactor, gas separators)

CO₂ acquisition is a batch process so 2 systems operate in parallel so one is freezing CO₂ while the other is heating & venting to the Sabatier. The Sabatier is an exothermic reaction so one time power draw then self-sustaining. Products go through 2 separation systems to remove water product and excess H₂...both are recycled back to Sabatier.

Cryocoolers for CO₂ capture 4per module, CO₂ gas at 50psia to drive system.

Excavator: (rovers only)

Rovers operate 24/7 to maintain needed H₂O production rate: battery recharge time and traverse time included in rate calcs.

Rassor, 1 per module, Traveling 100m at

0.26m/s,

Capacity 0.05m³ per batch (80kg)

Driers: (CH₄ drier, O₂ drier)

Regenerative desiccant systems remove excess water prior to liquefaction. Some product is lost during regeneration, but this margin accounted for in production rate.

Electrolysis: (Delonizer, PEM stack, pumps, H₂/H₂O separator tank)

Cathode feed PEM stack feed by regolith water and water from Sabatier reactor.

PEM: 1 stack (+1 spare) per module, 71 cells, baseline operation at 1.8V

Regolith processing: (hoppers, reactor, water vapor cleanup, water capture)

Rovers deliver to hopper/size sorter which meters regolith to the screw conveyor reactor to maintain continuous reaction. Water vapor periodically builds pressure to 20psia and vents to condenser for capture as liquid.

Reactor: 1 per module

Water condenser w/ passive cooling at operation saturation temp¹300K)

